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Influence of massive heat-pump introduction on the electricity-generation mix and the GHG effect: Comparison between Belgium, France, Germany and The Netherlands

Patrick J. Luickx, Lieve M. Helsen, William D. D'haeseleer*

Division of Applied Mechanics and Energy Conversion, Katholieke Universiteit Leuven, Celestijnenlaan 300A, box 2421 B-3001 Leuven, Belgium

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Abstract

To evaluate the environmental impact of massive heat-pump introduction on greenhouse gas (GHG) emissions in different electricity-generation systems, dynamic simulations have been carried out for four European countries, namely, Belgium, France, Germany and the Netherlands. For this purpose, the simulations are performed with Promix, a tool that models the overall electricity-generation system. Three heating devices are considered for each country, namely classic fossil-fuel heating, heat pumps and electric resistance heating. Both direct heat-pump heating with a coefficient of performance (COP) of 2.5 and accumulation heat-pump heating with a COP of 5 are investigated. The introduction of electric heating in an electricity-generation system increases the demand for electricity and generates a shift of emissions from fossil-fuel heating systems to electrical plants. The results of the simulations reveal that the massive introduction of either heat pump or resistance heating is always favourable to the environment in France. The most environmentally friendly scenario in 2010 is projected to reduce GHG emissions by about 3.8 Mton compared to the reference scenario. In Belgium and Germany, the largest reduction in GHG emissions occurs with accumulation heat pumps. Belgium can save up to 220 kton of GHG emissions, while Germany can attain reductions of 800 kton in 2010. In the Netherlands, a significant reduction can be achieved

Abbreviations: CC, combined cycle; COP, coefficient of performance; GHG, greenhouse gases; IEA, International Energy Agency; kWh_e, electric kWh; kWh_{th}, thermal kWh; LHV, lower heating value

*Corresponding author. Tel.: +32 16 32 25 11; fax: +32 16 32 29 85.
E-mail address: William.Dhaeseleer@mech.KULeuven.edu (W.D. D'haeseleer).

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by considering the addition of gas-fired combined cycle (CC) power plants, together with the introduction of electric heating, resulting in emissions savings of 410 kton.

Keywords: Heat pump; Greenhouse gas (GHG); Electricity-generation system; Belgium; France; Germany; The Netherlands; Dynamic simulation; Promix

Contents

1. Introduction

This paper compares the environmental impact of a massive heat-pump introduction for Belgium, France, Germany and the Netherlands. As has already been investigated in a previous paper [1], partly replacing classic fossil-fuel heating systems by heat pumps or electric resistance heating has an effect on the greenhouse gas (GHG) emissions. The increased demand for electricity due to a shift from conventional to electric heating will reallocate emissions from fossil-fuel heating systems to electric power plants. Apart from a reference scenario, direct heat-pump heating with a moderate system coefficient of performance (COP) of 2.5, accumulation heat-pump heating[1] with an elevated system COP of 5 and direct resistance heating are investigated for the years 2000 and 2010.[2]

In a general context, this study aims to provide a deeper insight on the interaction between electricity-generation systems and electricity demand. More specifically, the effect of the relation between demand-profile changes and varying electricity supply on the GHG emissions is studied. Just as in previous work done on this topic [1], where the Belgian electricity system was considered, the focus is now on the operation characteristics of the

[1]The idea of accumulation heating is the utilisation of electric power generated off-peak, mainly during night-time, for heating purposes during daytime.

[2]The choice of the years 2000 and 2010 should not be seen as a realistic timeframe for massive heat-pump introduction but rather as an indication on how the evolution of an electricity-generation system over a certain amount of time will impact the operation of the system and the ensuing emissions.

different electricity-generation systems of the four countries mentioned, not on the investment decision or related costs of electric heating.

This paper adopts the same dynamic approach that simulates the operation of the electricity-generation system as in [1]. The full impact of a measure and not merely the static increment is looked at. To evaluate the impact of heat pumps and electric resistance heating on each country, the dynamic simulations are based on the actual electricity-generation system composures of the respective countries. Regarding previous insights concerning this topic, Voorspools and D'haeseleer [2,3] are referred to. Overviews of modelling strategies for unit commitment scheduling can be found in Sen and Kothari [4] and Voorspools and D'haeseleer [5].

2. Methodology

To perform the required simulations, the Promix tool is used. Promix stands for "Production Mix" and refers to the detailed composition of the electricity-generation system in a particular country. Promix calculates the cost-optimal usage of the available power plants to cover the varying electricity demand. This is achieved by establishing a merit order for all available plants, based on minimal marginal fuel costs. The tool takes into account the composition of the electricity-generation system, the fuel costs and other country-specific parameters so as to offer a realistic simulation of the considered systems. The Promix output consists of the hourly electric power generated by each separate power plant, as well as the corresponding energy use, costs and emissions. The Promix features make it a suitable tool for the evaluation of policy decisions on electric applications, such as the massive introduction of heat pumps in an energy system.

A detailed description of Promix goes beyond the scope of this paper. Further details can be found in studies performed by Voorspools and D'haeseleer [2,3]. In what follows, an overview of the most relevant input features of Promix is provided.

3. Promix input

3.1. Modelling the electricity-generation systems

For each of the four countries considered, namely Belgium, France, Germany and the Netherlands, detailed data on the electricity-generation system are required. Promix needs several plant-specific data as input. Promix considers technical restrictions of power plants such as marginal costs, instantaneous emissions, minimum-operation point, minimum up and down time of a plant. In addition, the total amount of installed capacity of each type of power plant needs to be established. After careful research, the Belgian, French, German and Dutch electricity-generation systems have been modelled. The installed electricity-generation capacity for the different countries is represented in Tables 1 and 2 for 2000 and 2010 respectively. The year 2000 is based on the actual composition at that time; the year 2010 represents a plausible extrapolation. For the purpose of this paper where focus is put on the methodological aspects of CO_2-emission variations due to different electricity-generation systems, the exact composition of the system in 2010 is not an issue.

Belgium is probably the most balanced electricity-generation system of the four countries considered. In 2000, Belgium counted three major groups of power plants.

Table 1
The installed capacity (in MW) in the electricity-generation systems of Belgium, France, Germany and the Netherlands in 2000

Electricity-generation system	2000 (in MW)			
	Belgium	France	Germany	The Netherlands
Total	14,450	100,800	111,920	21,100
Nuclear	5700	62,600	22,000	450
Coal-fired	2000	9600	29,500	4200
Lignite	–	–	20,320	–
Gas-fired, combined cycle (CC)	2670	–	2730	1800
Gas-fired, classic	1900	1850	7580	4480
Oil-fired	150	9350	950	500
Blast furnace	920	–	–	820
Cogeneration	940	5200	18,700	7870
Renewables	170	12,200	10,140	980

Table 2
The installed capacity (in MW) in the electricity-generation systems of Belgium, France, Germany and the Netherlands in 2010

Electricity-generation system	2010 (in MW)			
	Belgium	France	Germany	The Netherlands
Total	16,400	109,900	131,330	24,960
Nuclear	5700	62,600	18,500	450
Coal-fired	1510	5850	30,700	4200
Lignite	–	–	21,600	–
Gas-fired, combined cycle (CC)	5470	8000	2730	3000
Gas-fired, classic	900	1850	4300	3850
Oil-fired	–	4780	950	500
Blast furnace	720	–	–	820
Cogeneration	1700	6400	23,700	8820
Renewables	400	20,420	28,850	3320

The nuclear power plants, with their high utilisation rate, provide base-load power and supply about half of all generated electricity. The second group consists of gas-fired CC units with a relatively high efficiency and interesting modulating capacities. The third group comprises classic thermal power stations with varying utilisation rate and fuel type, which operate mainly with coal. Belgium has only a limited amount of renewable energy plants due to unfavourable conditions and corresponding low potential for renewables. Cogeneration is a technology that is rapidly gaining ground in the Belgian electricity-generation system. Belgium also disposes of water pumping units of about 1300 MW that enable a more efficient operation of base-load electricity produced off-peak which can be stored to meet peak demand.

As Table 1 clearly illustrates, the most striking particularity of the French electricity-generation system is the importance nuclear power plays in the provision of electricity. In 2000, nuclear power represents about 60% of total installed capacity in France and around

three quarters of the total amount of generated electricity. Owing to the relatively low operating costs, nuclear power practically operates as base load in France. Only during periods with low demand for electricity, such as the summer period, a number of nuclear plants are put on hold. A significant amount of the installed capacity of nuclear power plants can be modulated for this purpose. Apart from nuclear power, France also relies on conventional power plants, especially on coal plants. Oil-based power plants mainly act as reserve and are only used when demand is at its highest. The relatively important amount of renewables with more than 10,000 MW of installed hydropower facilities, provide little over 10% of the electricity within the hexagon. A last noteworthy portion of the electricity provision is covered by combined heat and power plants, using several possible fuel types. A striking fact is the absence of large sources of gas-driven power plants such as combined cycle (CC) power plants. However, given the vast amount of nuclear coverage, there is little need for it at the moment. Water pumping units and large water reservoirs allow for a more efficient operation of the French electricity-generation system. The capacity of this type of reservoir plants is situated around 13,000 MW.

Where the nuclear generation capacity is characterising France, the German electricity production heavily relies on lignite and hard coal, both widely available as a resource in Germany. Together they represent about half of the total German electricity generation in 2000. German nuclear power plants account for about 30% of the generation and operate as base-load power plants. Gas-fired plants, mainly combined heat and power, and renewable energy cover almost all of the remaining electricity provision. The drawback of Germany depending on coal is that the GHG emission rate of Germany is considerably higher than in neighbouring countries such as France or Belgium. Germany has about 5600 MW of water pumping units at its disposal.

The Dutch electricity-generation system is to a large extent gas dependent. Apart from regular and CC gas-fired plants, the Netherlands has a vast amount of installed combined heat and power plants. In total, about 60% of the generated electricity stems from gas sources. Besides gas-driven power plants, there is still an important share of coal plants that contribute to the electricity generation in the Netherlands. Coal-driven power plants represent almost 30% of the total electricity generation. Renewable sources, nuclear power and oil provide the remaining amount of electricity. The Netherlands has the highest share of decentralised power-generation capacity in the European Union. The largest portion is made up by gas-driven combined heat and power plants. Renewable energy sources, mainly wind turbines, and waste incinerators are also part of the Dutch decentralised electricity-generation capacity.

Towards 2010, Belgium will likely increase its capacity for efficient gas-fired CC plants, which can clearly be seen by comparing the values of 2010, as in Table 2, with the 2000 figures of Table 1. Most investments in the Belgian electricity-generation system will be CC gas-fired plants and combined heat and power (CHP) plants. These will partly replace older and less efficient plants and partly meet the rise in demand for electricity.

For our model 2010 system, France is supposed to close down some of its older oil and coal plants, while investing in gas-fired capacity such as CC plants and cogeneration units. Furthermore, a significant increase in electricity provision from renewable sources is assumed to occur, mostly due to the commissioning of wind turbines.

In Germany, the coal-fired generation is expected to slightly expand towards 2010. On the other hand, the country has decided to phase out nuclear power over the next two decades. The investments in new power plants will mostly occur in gas-fired power

generation and renewables. Germany is one of the countries that most actively invest in wind turbine sites. Towards 2010, the target set by the government is to reach 22,000 MW of installed wind power capacity. Also, concerning other sources of renewable energy, such as biomass and biogas, Germany is considered to be a pacesetter.

Towards 2010, the Netherlands may be expected to further expand the gas-driven generation capacity. Approximately 1 GW of new combined heat and power and 1.2 GW of CC power plants are planned by 2010. The country is also planning on extending the investments in renewable energy sources. In the development of the electricity-generation system, 2.5 GW of installed wind power capacity could be available in 2010.

Because import and export changes are difficult to predict and since the aim of this paper is to analyse the dependency of the GHG emissions due to the dynamics of the generation system, the assumption is made that import and export remain unchanged in 2010 compared to 2000.[3] Belgium is a net importer of electricity, with an import of 1.17 TWh in 1999 according to the IEA country report of 2001 [7]. France is an important exporter of electricity. According to the IEA country report of 2004 [8], the net export of France reached about 70 TWh in 2001. This amount is presumed to apply to the years 2000 and 2010. The net import of Germany in 2000 was reported to be 3.5 TWh according to the IEA country report of 2002 [9]. The considerable net imports of the Netherlands reached 17.5 TWh in 2001 [10]. This amount is used for both 2000 and 2010.

3.2. Heat-demand pattern

A simple sine-wave heat-demand pattern is displayed in Fig. 1. It is used for all performed Promix simulations related to domestic heating problems [1]. The figure represents the hourly demand for heat during an entire year and clearly distinguishes daytime demand from the night regime. The night is taken to start at 10 p.m. and to end at 6 a.m. Fig. 1 is scaled to 1 MWh/h, which is also the peak demand in the displayed representation. This scale is multiplied by a factor, according to the scenario under consideration and its accessory demand for electric heating.

The time dependency of electricity will influence the GHG emissions to a great extent. With a shift from conventional to electric heating, the electricity demand pattern will undergo a change of the order of the heat-demand pattern. In the different scenarios, the situation without additional electric heating is compared to one with extra electric heating, so as to evaluate the effect of the fossil-to-electric shift on GHG emissions.

3.3. Fuel price

Since Promix calculates the most effective usage of power plants to cover the electricity demand according to minimal marginal fuel costs, fuel prices are a major driver of the generated results. A clear understanding of the current fuel prices and sound assumptions regarding the future fuel price evolution is necessary. Sensitivity analyses on fuel prices have been performed for Belgium in [1] and it can be concluded that relatively higher gas prices will lead to more GHG emissions due to increased usage of more polluting power plants. The same reasoning applies to France, Germany and the Netherlands.

[3]This assumption has been made for simplicity. The effect of changes in import and export on GHG emissions is considered in [6].

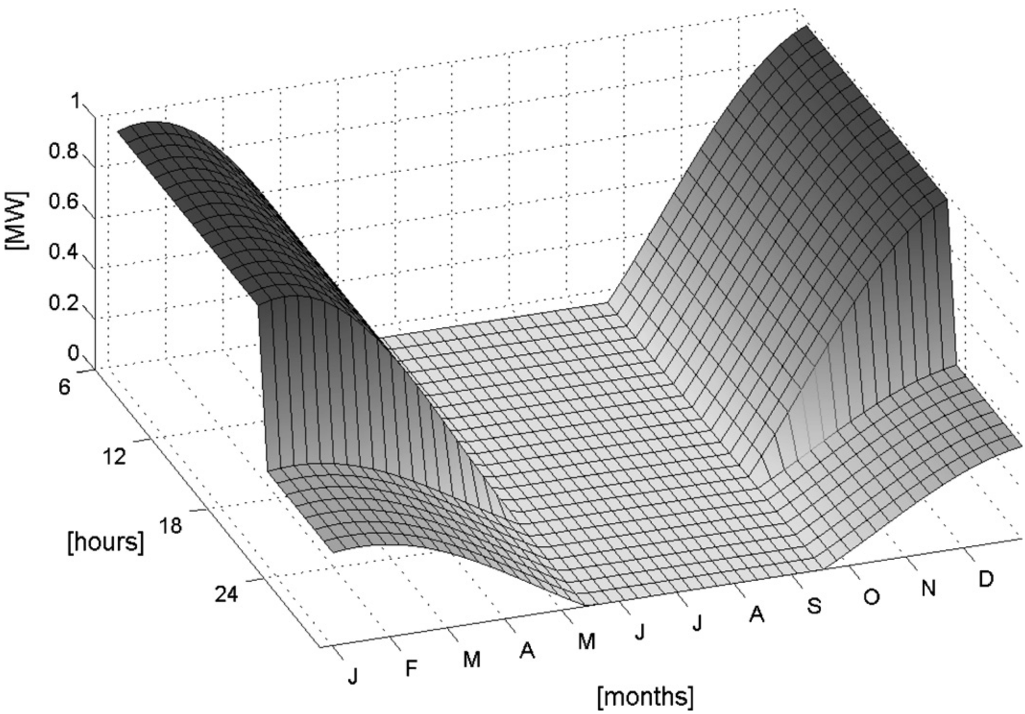

Fig. 1. Normal heat-demand profile for domestic heating. The maximum amount has been set equal to 1 MW to allow for easy scale-up.

Promix simulates the years 2000 and 2010 for all the different scenarios. Regarding 2000, actual fuel price values have been used in the performed simulations. However, the year 2010 is characterised by an uncertainty regarding fuel prices. The projections made by the IEA in their World Energy Outlook 2004 [11] have been taken as probable values for the fuel price developments towards 2010. These forecasts can be considered to represent a relatively low increase in fuel prices. The fuel prices are assumed to be identical for all four countries. This allows for a better ground for comparison between the relevant countries.

4. Scenarios for the massive introduction of heat pumps

To evaluate an electrical application, it is necessary to compare the effect of the introduction of this application to a situation without its massive introduction. This enables the direct attribution of extra GHG emissions or a change in primary energy usage to the measure considered. Several heating options are therefore considered. Classic fossil-fuel fired heating, heat pumps and direct resistance heating are taken into account as done in preliminary simulations reported in [12]. Due to the replacement of conventional heating systems by electric applications, primary energy use and GHG emissions originating from conventional heating is avoided.

The amount of heat production by conventional heating that is replaced by electrical heating is chosen so as to generate a significant impact on electricity production. For the

Belgian case, the heat-demand profile is scaled to peak at 360 MWh_{th}/h.[4] Both the French and German electricity-generation system had around 100 GW of installed capacity in the year 2000. The heat-demand profile of both countries is scaled to reach a peak at 2700 MWh_{th}/h. An identical reasoning has been applied to the Dutch heat-demand profile, where a peak of 500 MWh_{th}/h is reached for a generation capacity of about 21 GW. In order to represent the heat demand that is replaced by electric heating, a factor of 360 for Belgium, 2700 for France and Germany and 500 for the Netherlands is applied to the aforementioned heat-demand pattern depicted in Fig. 1.

Two types of conventional heating are considered. Gas-fired boilers with an efficiency of 100% are presumed to have emissions of 200 g/kWh while oil-fired heating systems with an efficiency of 80% emit 340 g/kWh. The emission factors are taken from [13,14]. The different simulated scenarios are described as follows:

In the reference *scenario A*, no additional electric heating is installed. The electricity demand grows annually by 2% until 2005 and by 1.5% between 2005 and 2010 for the four considered countries. It is assumed that the conventional heating is covered for 50% by gas-fired boilers and for another 50% by oil-fired heating, which results in an average GHG emission factor of 270 g/kWh. The development of the electricity-generation system occurs as planned.

In *scenario B*, direct electric resistance heating will be installed to cover the previously specified amounts of heating needs originally covered by conventional heating. The efficiency of direct resistance heating is assumed to be 100%, and therefore 1 MW_{th} equals 1 MW_e. The use of these resistance heating devices will increase the total electricity demand, compared to the reference scenario A. The evolution of the electricity system between 2000 and 2010 occurs as in the reference scenario A.

In *scenario C*, heat pumps for direct heating with a COP of 2.5 are introduced to cover the heating previously produced by conventional systems. The evolution of the electricity-generation system occurs as in the reference scenario A.

Scenario D considers the introduction of accumulation heat-pump heating, with a COP of 5. The electricity will be produced during off-peak hours. The electricity-generation system will develop as in the reference scenario A. The COP factors of both scenarios C and D are described by Hammad and Abu Gharbia [15].

5. Simulation results of the different countries

The impact of the massive introduction of heat pumps and other electrical appliances that replace classic fossil-fuel heating systems is evaluated in this section. Each electricity-generation system has its own specificity, which will yield diverse results. Several indicators reveal the differences in GHG emission reduction of Belgium, France, Germany and the Netherlands for the years 2000 and 2010.

5.1. Average GHG emissions

The average GHG emissions (in g/kWh) of produced electricity for the four countries are represented in Fig. 2 In 2000, the Netherlands, with its significant 30% of coal-based

[4]The same proportions have been used as in a previous study on massive heat-pump introduction in Belgium [1].

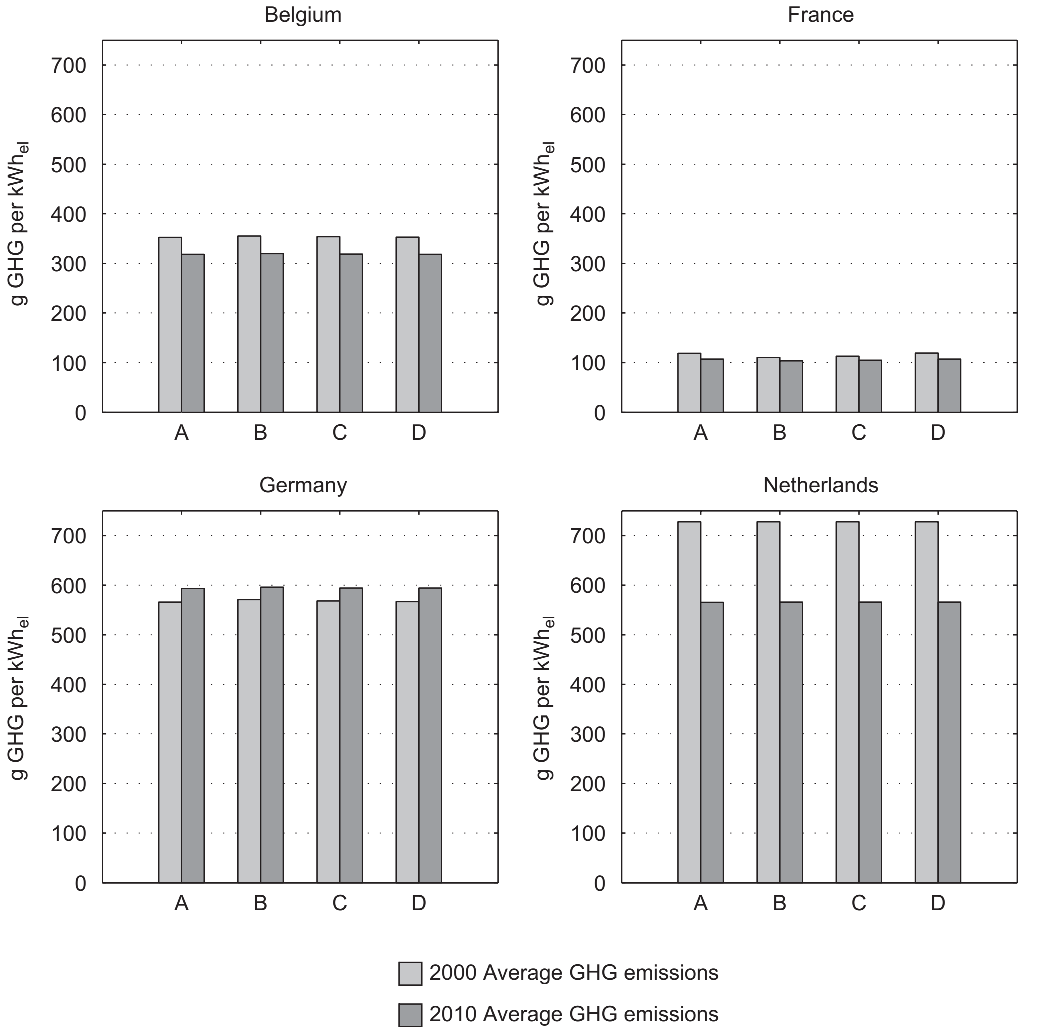

Fig. 2. The average GHG emissions resulting from electricity production in 2000 and 2010.

electricity generation and very little nuclear power generation, is observed as the country with the largest specific emission, while Germany is foreseen to take over this role in 2010. Because of the high share of nuclear power plants and an important amount of hydro-electric stations, the average GHG emissions of the French electricity-generation system, with values around 110 g/kWh$_e$, are by far the lowest for both years considered. Belgium situates itself somewhere in between these extremities with emission rates around 320 and 350 g/kWh$_e$ for 2000 and 2010, respectively.

All countries, except for Germany see their GHG emission rate decrease over the considered time span. This is due to the favourable development of the countries' electricity-generation systems towards higher shares of gas-fired power plants. Germany, however, plans on extending the already vast capacity of coal- and lignite-fired power plants and, importantly, Germany intends to phase out nuclear power. Whereas the

average German emissions are situated between 560 and 570 g/kWh$_e$ in 2000, they rise up to about 595 g/kWh$_e$ in 2010. The Netherlands undergo the most significant drop in average GHG emissions, owing to the increase in electricity demand over the 10 years being completely covered by efficient gas-fired power plants and renewables.

France is the only country that sees its emissions rate decrease with the introduction of electric heating. Where France can cover this rise in electricity demand with more nuclear power, the other countries have to rely on their less efficient and more polluting power plants, thus decreasing the overall efficiency of the electricity-generation system. For Belgium, Germany and the Netherlands, average emissions of scenarios B, C or D, rise or remain constant compared to the reference scenario.

5.2. Total GHG emissions

Fig. 3 illustrates the total annual GHG emissions of the four countries for each of the scenarios for both 2000 and 2010. To perform an adequate comparison between the reference scenario and the other scenarios, it is necessary to add the avoided GHG emissions originating from fossil-fuel conventional heating to the reference scenario. This way the total avoided GHG emissions can be evaluated. The amount of heat, originally produced by conventional heating that is being generated by different forms of electric heating in scenarios B–D varies according to the country considered. In Belgium, the replaced conventional heating represents about 1 TWh$_{th}$ per annum; in France and Germany, it amounts to almost 7.3 TWh$_{th}$ per year; while the Netherlands see its needs for classic fossil-fuel fired heating decrease by approximately 1.4 TWh$_{th}$ over a year.

All the countries have in common that scenario D, considering accumulation heat pump heating, always generates a reduction in GHG emissions compared to the reference scenario. Scenario C with heat pumps for direct heating, results in a decrease of overall GHG emissions in every country, except in Germany. Germany relies heavily on coal- and lignite-based electricity generation. Only the most efficient technology, the accumulation heat pump with a COP of 5, renders a positive outcome due to the relatively low increase in electricity demand for a certain rise in electricity-based heating.

In Belgium and the Netherlands as well, the accumulation heat pump brings about the largest reduction in GHG emissions in both 2000 and 2010. The reasoning behind this is that, although the average GHG emissions of the electricity-generation systems are rising with the introduction of more electrical appliances, this rise will be offset by the avoided emissions coming from conventional heating. The COP of heat pumps causes the rise in electricity usage not to be as high as the corresponding heat provision. The option of introducing direct resistance heating shows a negative outcome regarding GHG emissions for both countries.

Fig. 3 reveals that for France, all scenarios, for both 2000 and 2010, generate less GHG emissions than the reference scenario. Also noteworthy is that France is the only country where the introduction of heat pumps with higher COP leads to higher emissions than a more electricity-intensive alternative, with scenario B being the most environmentally friendly option. The most notable observation, however, is the fact that even when taking only the GHG emissions originating from the electricity-generation system, a decrease can be observed. At first this may seem contradictory since scenarios B–D introduce additional electric applications and a coinciding elevated demand for electricity. However, France has the particularity of operating with modulating nuclear power capacity, which will be

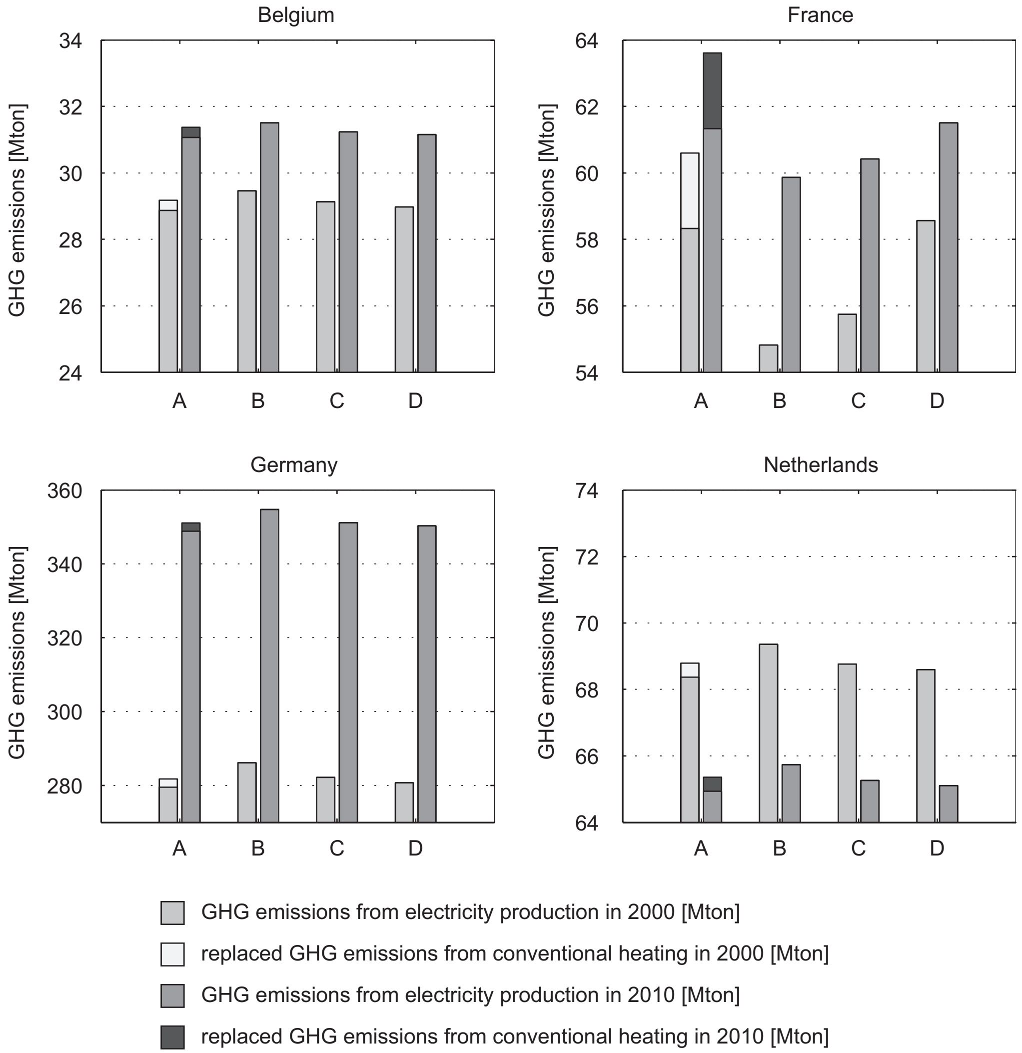

Fig. 3. Total GHG emissions for scenarios A–D; additional GHG emissions of replaced conventional heating are accounted for in scenario A in 2000 and 2010. Please note the different vertical scales for the four cases.

addressed more frequently under the conditions in these scenarios. Nuclear power plants cover the increase of the electricity demand while at the same time outperforming coal-fired power stations. This double increase in the use of nuclear power plants can be explained by the technical characteristics of nuclear plants. Since they already operate more intensively because of the rise in electricity demand, it becomes less interesting to shut them down for shorter periods. An operating nuclear plant will always be more profitable than having to start up a classic thermal power plant such as coal-fired power stations. The effect is most pronounced in scenario B, which corresponds to the scenario with the largest increase in electricity demand during peak moments.

5.3. Relative change in GHG emissions

Fig. 4 depicts the changes in GHG emissions originating from the electricity-generation system between the reference scenario and the other scenarios relative to the change in electric and heat provision for the year 2010. The first of each pair of bars in Fig. 4 characterises the change in average GHG emissions for each extra kWh of electricity produced. The second bar defines the change in average GHG emissions per kWh of additional electric heating. A negative value for one of these bars stands for a certain decrease in GHG emissions per extra kWh of electricity or heat production. The change in GHG emissions per kWh of added electric heating, can be compared to the previously mentioned emission factors of the conventional boilers, which amount to 200 and 340 g of

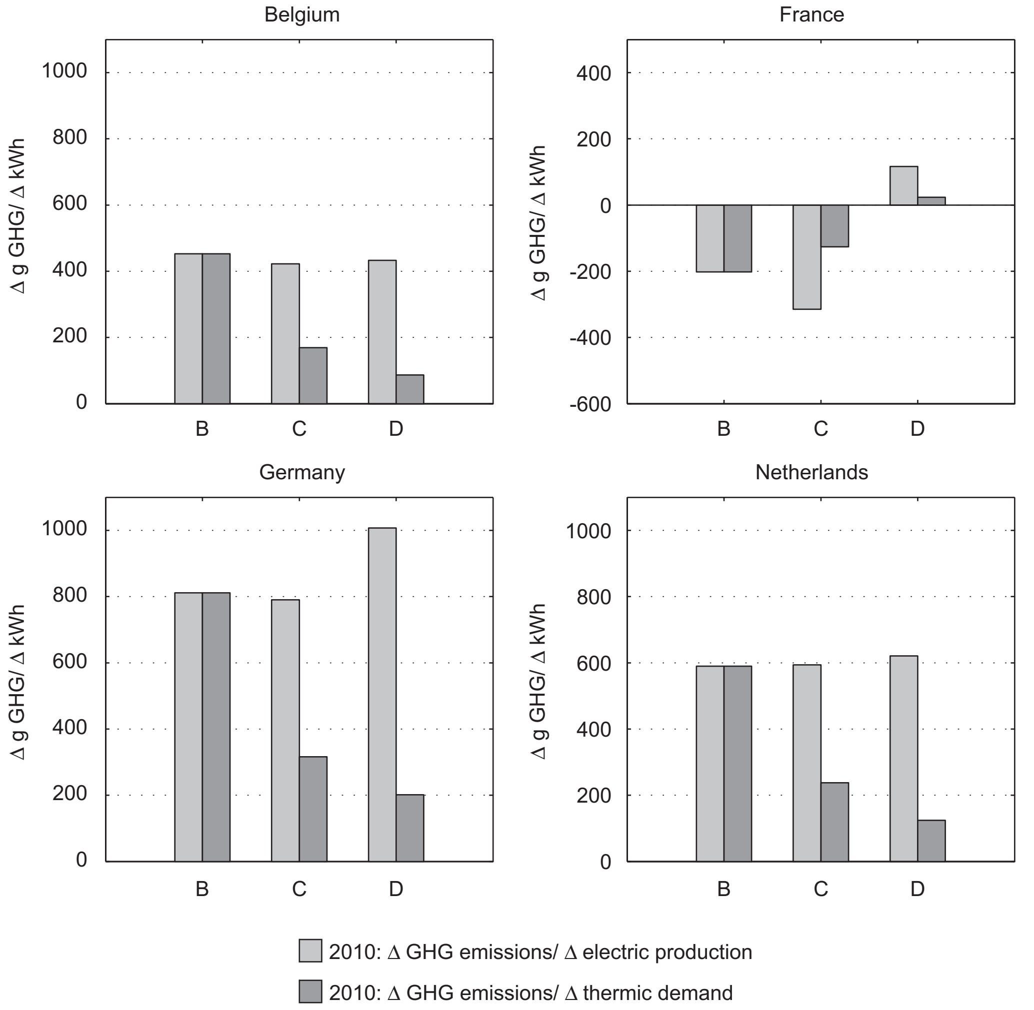

Fig. 4. The change in GHG emissions related to electricity production change and change in electricity-generated heat provision in 2010.

GHG emissions per kWh for gas-fired and oil-fired heating systems, respectively, leading to an average classic heating emission factor of 270 g/kWh$_{th}$.

France is the only country showing negative numbers. Every addition of either direct resistance or heat-pump heating generates a reduction in GHG emissions. For every kWh$_{th}$ of heat provisions that is transferred from classic heating to direct resistance heating, not only a saving of 270-g GHG emissions is realised; an extra reduction of 200 g/kWh$_{th}$ is achieved as well. This reduction in electricity-generated GHG emissions originates from the previously mentioned higher usage of modulated nuclear power. For the considered amount of direct resistance heating, a total reduction of 470 g/kWh$_{th}$ can be noted compared to the reference scenario. Although the accumulation heat pumps scenario shows a positive emission factor, it is still well below the average factor of conventional heating.

In Germany, only scenario D will generate an increase in GHG emissions per kWh of heat produced by heat pumps that is lower than the average emission factor of boilers, thus constituting a good replacement option. In Belgium and the Netherlands, both scenarios C and D generate an emission factor lower than 270 g/kWh$_{th}$. After France, Belgium is the country with the lowest emission factor for scenarios C and D. This is mainly due to the significant amount of electricity generated out of nuclear power, compared to the Netherlands and Germany.

6. Additional combined cycle power plants

The massive introduction of heat pumps generates a significant impact on each of the electricity-generation systems. The need for classic fossil-fuel heating decreases, whereas less efficient or older power plants will cover the rise in electricity consumption. Such a shift and its impact on electricity demand, however, could justify the commissioning of new power plants as long as the overall peak demand of the system is not exceeded. Therefore, two additional scenarios, B+ and C+, where gas-fired CC power plants are added to the electricity-generation system are analysed as well.[5]

Scenario B+ only differs from scenario B in that the power system planning is altered with the commissioning of extra gas-fired CC capacity with an overall reliability of 90%. This measure is meant to cover the increase in electricity need. In Belgium, 400 MW$_e$ are added to the system. In France and Germany 3000 MW$_e$ are chosen to reinforce the electricity-generation system. In the Netherlands, 555 MW$_e$ of CC gas-fired plants is being invested in.

The second alternative, *scenario C+*, is a variation of scenario C. The system planning is also altered with the commissioning of additional gas-fired CC capacity. While an extra 160 MW$_e$ is installed in the Belgium system, 1200 MW$_e$ of CC gas-fired plant is added in France and Germany. The Dutch electricity-generation system is altered by an additional 222 MW$_e$ of a CC gas-fired plant.

The consequences of additional gas-fired CC power plants in 2010 can be derived from Fig. 5. In all cases considered, except for the direct resistance heating in France, the addition of gas-fired power plants brings about a reduction in overall GHG emissions, when compared to the same scenario without the extra commissioned plants. A gas-fired

[5]Note that a possible scenario D+ does not make sense as the accumulation heat pumps operate at night, when sufficient generating capacity is available.

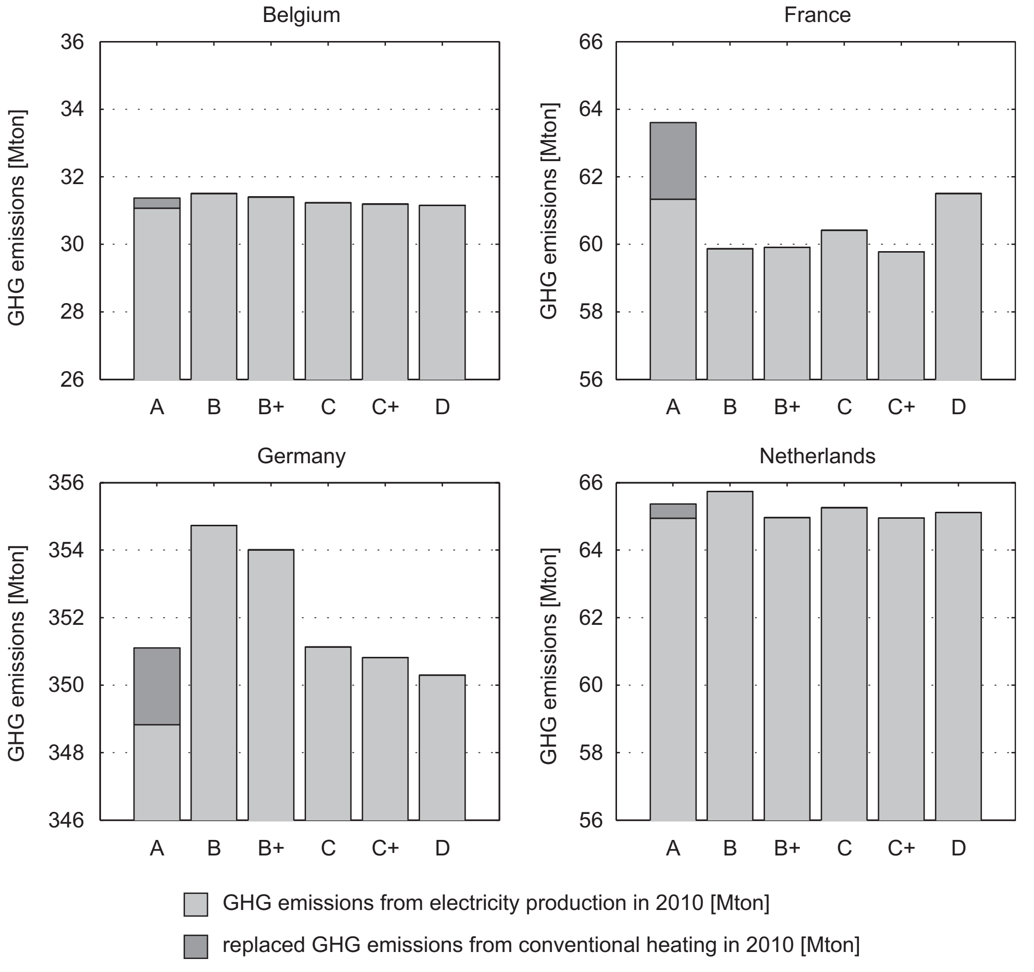

Fig. 5. Total GHG emissions for scenarios A–D in 2010; additional GHG emissions of replaced conventional heating are accounted for in scenario A in 2010. Please note the different vertical scales for the four cases.

CC power plant will usually improve the overall efficiency of the electricity-generation system.

This is definitely the case in the Netherlands, where both scenarios considering additional investments in gas-fired power plants emit the smallest amount of GHG. Any addition of gas-fired CC capacity results in an important reduction in GHG emissions. For the fuel prices chosen, the newly built CC power plants will practically operate in base load, not solely covering the rise in electricity demand but generating electricity all year round while outperforming older gas and coal power plants. In scenario B+, a switch of about 3500 MWh of produced electricity takes place from older coal and gas power plants to the 555 MW_e additional CC power plants, compared to scenario B. Scenario C+ results in the largest overall reduction of GHG emissions in the Netherlands due to the combination of the expansion of the electricity-generation system and the introduction of heat pumps.

Table 3
Results for 2010 of scenarios simulating the promotion of heat pumps in Belgium

	Reference 2010	Scenario C	Scenario C+	Scenario D
Annual electricity-related GHG emissions (Mton)	31.1	+0.164	+0.121	+0.084
Avoided emissions from fossil-fuel-fired applications (Mton)	–	−0.303	−0.303	−0.303
Electricity generation (TWh)	97.6	+0.388	+0.388	+0.194
Nuclear, renewable, CHP (TWh)	59.4	+0.02	+0.02	+0.03
Coal-fired (TWh)	10.0	–	–	+0.02
Gas-fired, CC (TWh)	26.6	+0.34	+0.40	+0.13
Gas, oil-fired classic (TWh)	1.6	+0.02	−0.03	+0.02

In France as well, scenario C+, generates the most favourable outcome, combining the increased use of relatively clean nuclear and gas-fired power and the efficient operation of heat pumps. However, the most important reason for GHG emissions reduction remains the increased utilisation rate of the nuclear power plants. Germany and Belgium are also affected by the commissioning of additional CC power plants. However, the effect of the efficiency of the heat pumps prevails. Scenario D remains the most GHG-reducing scenario with C+ being the second best option. For Germany, the addition of the CC plants ensures a reduction of GHG emissions with the introduction of heat pumps for direct heating. Where scenario C shows no amelioration compared to the reference scenario, scenario C+ becomes an interesting option regarding GHG emissions reduction.

A detailed output for the Belgian scenarios C, C+ and D is presented in Table 3 for 2010. The avoided 303 kton GHG emissions from conventional heating compensates for the rise in electricity-related emissions in each of the three considered scenarios. In scenario C+, the annual production of gas-fired CC plants rises by about 0.4 TWh, whereas the additional electric demand is only 0.388 TWh. The new CC plants will tend to run as base-load power, which is a positive development since the overall efficiency of the electricity-generation system is improved. However, the introduction of heat pumps remains the most important driver for GHG emissions reduction, with scenario D rendering the largest savings in GHG emissions.

In Table 4, a closer look is given to the introduction of heat pumps in 2010 in France. As mentioned before, a total of 2.27 Mton of GHG emissions are avoided by replacing 7273 GWh of heat production covered by conventional heating. Apart from this, an extra 0.92 or 1.56 Mton can be prevented in the electricity-generation system by using direct heat-pump heating to cover this replaced heat demand. When accumulation heat pumps are used, however, a small increase in electricity-related GHG emissions can be noted. In both heat pump cases, be it direct or accumulation heat-pump heating, an increased demand in electricity production can be noted. In scenario C, this increase is covered by a rise in the utilisation of nuclear power plants, which at the same time triggers a decrease in the usage of gas-, oil- and coal-fired power stations. In scenario C+, where an extra 1200 MW of gas-fired CC plants are installed, the rise in electricity generation is covered both by nuclear and gas-fired CC capacity, whereas the more polluting classic gas-, coal- and oil-driven power stations moderate their production. In scenario D, where the rise in electricity demand is situated off-peak, during the night, the increase in nuclear power

Table 4
Results for 2010 of scenarios simulating the promotion of heat pumps in France

	Reference 2010	Scenario C	Scenario C+	Scenario D
Annual electricity-related GHG emissions (Mton)	61.3	−0.916	−1.556	+0.170
Avoided emissions from fossil-fuel-fired applications (Mton)	–	−2.273	−2.273	−2.273
Electricity generation (TWh)	571.7	+2.884	+2.999	+1.455
Nuclear (TWh)	378.92	+4.59	+4.59	+1.19
Renewables and CHP (TWh)	130.32	–	–	–
Coal-fired (TWh)	32.76	−0.40	−0.42	+0.15
Gas-fired, CC (TWh)	21.85	−1.20	+0.13	+0.15
Gas, oil-fired classic (TWh)	4.18	−0.12	−1.30	−0.04

Table 5
Results for 2010 of scenarios simulating the promotion of heat pumps in Germany

	Reference 2010	Scenario C	Scenario C+	Scenario D
Annual electricity-related GHG emissions (Mton)	348.8	+2.299	+1.991	+1.466
Avoided emissions from fossil-fuel-fired applications (Mton)	–	−2.273	−2.273	−2.273
Electricity generation (TWh)	587.9	+2.909	+2.909	+1.455
Nuclear (TWh)	140.4	–	–	–
Renewables and CHP (TWh)	147.6	–	–	–
Coal- and lignite-fired (TWh)	294.2	+1.82	+1.54	+1.42
Gas-fired, CC (TWh)	3.9	+0.50	+1.57	−0.04
Gas, oil-fired classic (TWh)	1.7	+0.59	−0.21	+0.07

provision is lower than in C and C+. An explanation for this can be found in the lower increase in electricity demand for heat provisions because of the high COP that is assumed for accumulation heat-pump heating. Also, some of the increase in electricity demand is covered by other power plants.

In Table 5, the effect of introducing heat pumps in 2010 is represented more in detail for the case of Germany. Since the same amount of conventional heating replaced by electric heat pumps are considered as in France, the same saving in conventional heating emissions of 2.27 Mton can be observed as well. The difference between both countries lies in the effect of this increase in electricity demand on the electricity-related GHG emissions. Whereas some scenarios in France show a decrease in GHG emissions originating from electricity production, the German electricity-generation system always sees its emissions increased. In scenarios C+ and D, this increase is still compensated by the reduction of avoided classic heating emissions. Scenario C on the other hand has an overall increase in emissions. In the three scenarios considered, no increase is noted in nuclear, renewable energy or cogeneration power plant production, which constitute the base-load power. Although the increase in electricity demand in scenario D is practically entirely covered by polluting coal-fired power plants, the COP of the heat pump ensures a total reduction in GHG emissions. In scenario C+, the increase in power demand is double as high and

Table 6
Results for 2010 of scenarios simulating the promotion of heat pumps in the Netherlands

	Reference 2010	Scenario C	Scenario C+	Scenario D
Annual electricity-related GHG emissions (Mton)	64.9	+0.320	+0.008	+0.167
Avoided emissions from fossil-fuel-fired applications (Mton)	–	−0.421	−0.421	−0.421
Electricity generation (TWh)	97.6	+0.388	+0.388	+0.194
Nuclear (TWh)	3.4	–	–	–
Renewables and CHP (TWh)	52.2	+0.015	−0.024	+0.014
Coal-fired (TWh)	25.6	+0.079	−0.226	+0.101
Gas-fired, CC (TWh)	19.8	+0.043	+1.502	+0.055
Gas, oil-fired classic (TWh)	8.8	+0.403	−0.714	+0.099

almost equally spread over coal and lignite power plants and gas-fired CC power plants. Since the COP of the heat pump is lower than the one considered in scenario D, the overall reduction in GHG emissions will be lower.

Taking a closer look at the specific effect of heat pumps on the GHG emissions in the Netherlands, confirms what has been mentioned so far. Table 6 shows that the avoided GHG emissions of conventional heating amount to 0.42 Mton. On the other hand, every heat-pump scenario brings about a rise in electricity production and therefore in electricity-related GHG emissions. In scenario C+, this rise in GHG emissions originating from the electricity-generation system is almost non-existent. In this case, the COP of the heat pumps and especially the expansion of the power system both contribute to emissions reduction. By commissioning an additional CC power plant of 222 MW in scenario C+, this CC plant will not only cover the rise in demand for electricity but also replace the more polluting gas-, coal- and oil-based power plants. While the rise in electricity demand is only 0.39 TWh, the gas-fired CC capacity will see its production increased by 1.50 TWh. Scenarios C and D render a positive outcome because of the COP of the heat pumps. Scenario D has the highest COP and the accessory largest reduction in GHG emissions of both scenarios.

7. Summary and overall conclusions

The dynamic response on the electricity-generation system of massive heat-pump introduction and the ensuing environmental impact in Belgium, France, Germany and the Netherlands, has been investigated in this paper. A different conclusion stands for each of these countries.

The simulations indicate that a decrease in overall GHG emissions will result from the planned scale of heat-pump introduction in Belgium. This GHG emissions reduction is triggered by the COP of heat pumps. Moreover, adding gas-fired CC power plants showed to contain emissions-lowering potential as well. Of all scenarios considered, the best options, when only considering GHG emissions reduction, are the direct heat pump combined with the commissioning of new gas-fired CC plants and the accumulation heat-pump heating. These scenarios largely compensate the higher GHG emissions originating from electricity production by avoiding GHG previously emitted by conventional heating.

Several conclusions can be drawn from the results of the Promix simulations for France. Firstly, it is interesting to switch to electric heating in practically each scenario considered, almost solely due to the fact that an increase in electricity demand of this proportion triggers an increased usage of nuclear power stations. France disposes of a significant amount of dispatchable nuclear power capacity, which will operate under a higher usage rate with increasing demand for electricity. Operational nuclear power plants will be used to their fullest extent, thus outperforming other thermal power plants both on fuel cost and GHG emissions. Since nuclear power stations are supposed not to emit any GHGs, this will significantly reduce the overall GHG emissions. Secondly, it can be noted that the scenarios considering an expansion of the capacity in gas-fired CC power plants, namely scenarios B+ and C+, generate an even further decrease in GHG emissions. An increase in gas-fired CC plants allows for a shift from coal to the cleaner gas-based electricity production.

The Promix results for Germany show a much less interesting outcome concerning the replacement of conventional heating by electric heating appliances. Replacing fossil-fuel fired heating appliances by electric heating usually leads to higher overall emissions. Only the most efficient heat-pump scenario delivers a reduction in GHG emissions, while still providing the same amount of heat. In this context it is not surprising that scenarios D and C+ generate the best results. This is due to the COP of the heat pumps, which allows for efficient operation of the electricity consumed.

The Netherlands is characterised by an electricity-generation system with high GHG emissions. In 2000, it has the highest emission rate of the three countries considered. An assumed expansion of gas-fired capacity will considerably reduce the average GHG emissions by 2010. Likewise, the main conclusion that can be made for the Netherlands is that any addition of gas-fired CC power plants will bring about a reduction in GHG emissions. Since the new additional gas-fired CC plants will be technologically advanced and more efficient, they will tend to operate as base-load plants for the assumed fuel prices. The introduction of heat pumps in the Dutch heating system will also generate lower overall GHG emissions, be it with less impact than by adding CC power plants to the system.

There is a constant for each of the four countries considered. The scenarios introducing direct heat-pump heating together with extra gas-fired CC power plants and the scenarios considering accumulation heat-pump heating all generate an overall reduction of GHG emissions for the countries. Often, these scenarios will render the most positive results regarding GHG emissions. The reasons for this can be found in the COP of heat pumps and the availability of relatively clean gas-fired CC plants. A higher COP reduces the required amount of kWh_e for every kWh_{th}, whereas a newly built gas-fired CC power plant will be beneficial because it will tend to operate throughout the year, outperforming more polluting power plants and not exclusively providing electricity for heat pumps. The overall conclusion is that for Belgium, France, Germany and the Netherlands, the installation of a significant amount of heat-pump heating, will generate a positive effect on the environment.

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